Steel for mechanical parts, method for producing mechanical parts from said steel and the thus obtainable mechanical parts

Technical field

The invention relates to the field of steel metallurgy and, more particularly, steels for mechanical components, such as pinions.

Background to the invention

Steels for gear manufacturing must have a high level of resistance to contact fatigue. Most of the time, components produced from these steels are subjected to a carburizing or carbonitriding treatment which is intended to provide them with sufficient surface hardness and mechanical strength whilst maintaining a high level of core strength owing, in particular, to a carbon content in the order of from only 0.10 to 0.30%. The carbon content of the carburized layer may be up to approximately 1%.

Various documents describe gear manufacturing steels which are intended to be carburized. These include US-A-5 518 685, in which the contents of Si and Mn are maintained within relatively low limits (from 0.45 to 1% and from 0.40 to 0.70%, respectively) in order to prevent intergranular oxidation during the carburizing operation. JP-A-4-21757 describes steels for gear manufacturing which are intended to be carburised using plasma or at reduced pressure then shot blasted, and which can have contents of Si and Mn higher than the previous steels. They have a high level of resistance to the surface pressure acting on the pinion whose life span is thus increased.

WO-A-03 012 156 proposes a steel for mechanical components, such as pinions, the composition of which is: $0.12\% \leq C \leq 0.30\%$; $0.8\% \leq Si \leq 1.5\%$; $1.0\% \leq Mn \leq 1.6\%$; $0.4\% \leq Cr \leq 1.6\%$; $Mo \leq 0.30\%$; $Ni \leq 0.6\%$; $Al \leq 0.06\%$; $Cu \leq 0.30\%$; $S \leq 0.10\%$; $P \leq 0.03\%$; $Nb \leq 0.050\%$. This steel has the advantage of minimising the operational plastic deformations of the component as a whole owing, in particular, to a judicious balance of the contents of silicon and manganese. The carburizing or the carbonitriding must preferably take place under non-oxidizing conditions, for example, at reduced pressure, so that the relatively high contents of silicon and manganese do not lead to problems of intergranular oxidation.

Generally, the carburizing or carbonitriding takes place at a temperature in the order of from 850 to 930°C. However, the current tendency is to attempt to carry out this operation at higher temperatures (high-temperature carburising or carbonitriding) in the order of from 950 to 1050°C. This increase in the processing temperature either allows the length of the processing time to be reduced with the same carburized depth or allows the carburized depth to be increased with the same length of processing time. The manufacturer thus has the choice of being able to increase the productivity of the installation or increase the effectiveness of the products obtained.

However, the application of a high-temperature carburizing or carbonitriding operation to the known steels which have been described presents a number of problems. Firstly, the high temperature may lead to an increase in poorly controlled grains, which is detrimental to the mechanical properties of the

component. Secondly, the carburizing or carbonitriding is followed by quenching during which the component is subjected to deformations. These may require the component to be remachined or, in the most extreme cases, cause it to be rejected. These problems are accentuated when the quenching is carried out on a component which has just been subjected to a carburizing or carbonitriding operation at high temperature and not at a more normal temperature.

The object of the invention is to provide, for metallurgists carrying out high-temperature carburizing or carbonitriding of mechanical components, in particular pinions, a steel which overcomes the problems mentioned above whilst maintaining the required mechanical properties, and which is also compatible with the carburizing and carbonitriding operations carried out at more normal temperatures.

Summary of the invention

To this end, the subject-matter of the invention is a steel for mechanical components, characterised in that the composition thereof is, in percentages by weight:

- $0.19\% \leq C \leq 0.25\%$;
- $1.1\% \leq Mn \leq 1.5\%$;
- $0.8\% \leq Si \leq 1.2\%$;
- $0.01\% \leq S \leq 0.09\%$;
- trace levels $\leq P \leq 0.025\%$;
- trace levels $\leq Ni \leq 0.25\%$;
- $1\% \leq Cr \leq 1.4\%$;
- $0.10\% \leq Mo \leq 0.25\%$;
- trace levels $\leq Cu \leq 0.30\%$;
- $0.010\% \leq Al \leq 0.045\%$;

- $0.010\% \leq Nb \leq 0.045\%$;

- $0.0130\% \leq N \leq 0.0300\%$;

- optionally trace levels $\leq Bi \leq 0.10\%$ and/or trace levels $\leq Pb \leq 0.12\%$

and/or trace levels $\leq Te \leq 0.015\%$ and/or trace levels $\leq Se \leq 0.030\%$ and/or trace levels $\leq Ca \leq 0.0050\%$;

the balance being iron and impurities resulting from the production operation, the chemical composition being adjusted so that the mean values J_{3m}, J_{11m}, J_{15m} and J_{25m} for five Jominy tests are such that:

$\alpha = |\ J_{11m} - J_{3m} \times 14/22 - J_{25m} \times 8/22\ | \leq 2.5$ HRC; and

$\text{\ss} = J_{3m} - J_{15m} \leq 9$ HRC.

Preferably, the composition thereof is adjusted so that

$\text{\ss} = J_{3m} - J_{15m} \leq 8$ HRC.

Preferably, the composition thereof is:

- $0.19\% \leq C \leq 0.25\%$;

- $1.2\% \leq Mn \leq 1.5\%$;

- $0.85\% \leq Si \leq 1.2\%$;

- $0.01\% \leq S \leq 0.09\%$;

- trace levels $\leq P \leq 0.025\%$;

- $0.08\% \leq Ni \leq 0.25\%$;

- $1.1\% \leq Cr \leq 1.4\%$;

- $0.10\% \leq Mo \leq 0.25\%$;

- $0.06\% \leq Cu \leq 0.30\%$;

- $0.010\% \leq Al \leq 0.045\%$;

- $0.015\% \leq Nb \leq 0.045\%$;

- $0.0130\% \leq N \leq 0.0300\%$;

optionally trace levels $\leq Bi \leq 0.07\%$ and/or trace levels $\leq Pb \leq 0.12\%$ and/or trace levels $\leq Te \leq 0.010\%$ and/or trace levels $\leq Se \leq 0.020\%$ and/or trace levels $\leq Ca \leq 0.045\%$, the

balance being iron and impurities resulting from the production operation.

Optimally, the composition thereof is:

- $0.20\% \leq C \leq 0.25\%$;
- $1.21\% \leq Mn \leq 1.45\%$;
- $0.85\% \leq Si \leq 1.10\%$;
- $0.01\% \leq S \leq 0.08\%$;
- trace levels $\leq P \leq 0.020\%$;
- $0.08\% \leq Ni \leq 0.20\%$;
- $1.10\% \leq Cr \leq 1.40\%$;
- $0.11\% \leq Mo \leq 0.25\%$;
- $0.08\% \leq Cu \leq 0.30\%$;
- $0.010\% \leq Al \leq 0.035\%$;
- $0.025\% \leq Nb \leq 0.040\%$;
- $0.0130\% \leq N \leq 0.0220\%$;

optionally trace levels $\leq Bi \leq 0.07\%$ and/or trace levels $\leq Pb \leq 0.12\%$ and/or trace levels $\leq Te \leq 0.010\%$ and/or trace levels $\leq Se \leq 0.020\%$ and/or trace levels $\leq Ca \leq 0.045\%$, the balance being iron and impurities resulting from the production operation.

The subject-matter of the invention is also a method for producing a mechanical component from carburized or carbonitrided steel, characterised in that a steel of the above-mentioned type is used for this purpose, on which a machining operation, carburizing operation or carbonitriding operation is carried out, then a quenching operation.

The carburizing or carbonitriding is preferably carried out at a temperature of from 950 to 1050°C.

The subject-matter of the invention is also a steel mechanical component, such as a gear component, characterised in that it is produced using the above method.

As will be appreciated, the invention is based on a precise adjustment of the content ranges of the main alloy elements, as well as the simultaneous presence, in well-defined contents, of aluminium, niobium and nitrogen.

The desired effects are substantially of two types.

Firstly, the selection of the contents of the main alloy elements is intended to achieve a Jominy curve with no significantly marked inflection point. This condition allows minimal deformations to be achieved during the quenching operation. In this respect, the carburizing or the carbonitriding which is carried out at high temperature is, as has been mentioned, particularly demanding.

It should be noted that the Jominy curve of a steel which is produced using a conventional standardised test characterises the quenchability of the steel. It is produced by measuring the hardness of a cylindrical test piece which has been quenched using a jet of water which sprays one of the ends thereof, along the length of one of the generating lines thereof. The hardness is measured at several distances x (in mm) from the sprayed end, and the corresponding value is designated J_x. J_{xm} refers to the mean value obtained during five tests for measuring the hardness at distance x.

As disclosed in document EP-A-0 890 653, to which the reader may refer for further details, the applicant demonstrated that a composition of the steel which produces a Jominy curve with no inflection point was advantageous for producing greatly reduced deformations during the quenching operation following a carburizing or carbonitriding operation. This Jominy curve with no inflection point is produced when the values J_{11m}, J_{3m}, J_{25m} and J_{15m} satisfy the following relationships:

- $\alpha = |\ J_{11m} - J_{3m} \times 14/22 - J_{25m} \times 8/22\ | \leq 2.5$ HRC;
- $ß = J_{3m} - J_{15m} \leq 9$ HRC, or preferably ≤ 8 HRC.

The composition of the steel according to the present invention is therefore adjusted so that this relationship is also produced in this instance.

The composition is also adjusted, in particular owing to the combined presence of aluminium, niobium and nitrogen in defined contents, so that the size of the grains remains controlled, even when the carburizing or the carbonitriding is carried out at high temperature.

Finally, the composition of the steel must of course provide the desired mechanical properties for the use of the component. The criteria to be monitored more particularly include the carburized depth (conventionally defined as the depth at which the measured hardness is 550HV), the deviation of hardness between the surface and the core of the carburized component, which must be as low as possible in order to minimize the deformations during quenching, and the core hardness which must be high so that the component responds effectively to stresses

during operation, and therefore, has a high level of strength
in terms of endurance and fatigue.

Brief description of the drawing

The invention will be better understood from a reading of the
following description, given with reference to the appended
drawing which shows the Jominy curves of four reference steels
and three steels according to the invention.

Description of preferred embodiments

The steel according to the invention is intended primarily for
producing mechanical components which are subjected to high
levels of stress, such as gear elements, and which are intended
to be carburized or carbonitrided (preferably at low pressure
or in a non-oxidizing atmosphere to prevent oxidation of the
most oxidizable elements), both at normal temperatures of
approximately from 850 to 930°C and at high temperatures in the
order of from 950 to 1050°C. These components must have a high
level of fatigue endurance, high strength, and must be only
slightly deformed during thermal treatments, such as the
quenching operation following the carburizing or carbonitriding
operation. It has the following composition (all the
percentages are percentages by weight).

The carbon content thereof is between 0.19 and 0.25%. These
contents are normal for gear manufacturing steels. Furthermore,
this range allows the contents of the other elements to be
adjusted, which allows the desired shape to be produced for the
Jominy curve. The minimum content of 0.19% is further justified
by the core hardness which can be achieved thereby after
quenching. At more than 0.25%, there is a risk that the

hardness will be too high to preserve the desirable machinability for the steel. The preferred range is from 0.20 to 0.25%.

The manganese content thereof is between 1.1 and 1.5%. The minimum value is justified by the production of the desired Jominy curve in conjunction with the contents of the other elements. At more than 1.5%, there is the risk of the appearance of segregations and also banding during the annealing operations. Furthermore, such a high content would bring about excessive corrosion of the heat-resistant coating of the steel ladle during the production operation. It would not be desirable to further restrict this range of contents since producing the precise grade desired in the steelworks could be excessively difficult. The preferred range is from 1.2 to 1.5%, preferably from 1.21 to 1.45%.

The silicon content thereof is between 0.8 and 1.2%. In this range, the desired shape of the Jominy curve can be produced in conjunction with the contents of the other elements. The minimum value of 0.8% is justified by the production of the desired core hardness, as well as by the limitation of the deviation of hardness between the surface and the core after carburizing or carbonitriding. At more than 1.2%, there is a risk that excessive segregations will appear since silicon, though it segregates itself only slightly, tends to accentuate the segregation of other elements. There would also be an increased risk of oxidation during carburizing or carbonitriding. The preferred range is from 0.85 to 1.20%, preferably from 0.85 to 1.10%.

The sulfur content thereof is between 0.01 and 0.09%, the minimum value is justified by the production of correct machinability. At more than 0.09%, there is a risk of an excessively substantial reduction in the hot forgeability. The preferred range is from 0.01 to 0.08%.

The phosphorus content is between trace levels and 0.025%. Generally, the standards in force tend to require a maximum phosphorus content of this order. Furthermore, beyond this value, there is a risk of interaction with niobium which renders the steel brittle during the hot molding and/or the continuous casting of the steel in the form of blooms or billets. The phosphorus content is preferably 0.020% at the most.

The nickel content thereof is between trace levels and 0.25%. This element, which is introduced intentionally at higher contents, would increase the cost of the metal unnecessarily. In practice, the nickel content which results naturally from the fusion of the raw materials of the casting could be sufficient, with no deliberate addition. The preferred range is from 0.08 to 0.20%.

The chromium content thereof is between 1.00 and 1.40%. In this range, in conjunction with the contents of the other elements, the desired shape of the Jominy curve can be produced. Furthermore, the minimum content of 1.00% allows a high level of core hardness to be produced. At more than 1.40%, the cost of the production operation would be increased unnecessarily. The preferred range is from 1.10 to 1.40%.

The molybdenum content thereof is between 0.10 and 0.25%. In
this range, in conjunction with the contents of the other
elements, the desired Jominy curve shape and core hardness are
produced. The preferred range is from 0.11 to 0.25%.

The copper content thereof is between trace levels and 0.30%.
Again in this instance, as for nickel, the content produced
after fusion of the raw materials is generally maintained
purely and simply. At more than 0.30%, the ductility and the
core strength of the component would be impaired. The preferred
range is from 0.06 to 0.30%, preferably from 0.08 to 0.30% so
as to optimise the shape of the Jominy curve and the hardness
after quenching.

The aluminium, niobium and nitrogen contents thereof must be
controlled within precise limits. These are elements which,
when interacting, bring about control of the fineness of the
metal grain. This fineness is desirable in order to produce a
high level of strength in the carburized or carbonitrided layer,
a high level of fatigue strength and a reduction of the
dispersion of the deformation during quenching. Furthermore, it
is also important for producing the desired shape for the
Jominy curve. Controlling the grain size is, in the context of
the invention, all the more important since the steel must be
capable of being subjected to a carburizing or carbonitriding
operation at high temperature without an excessive increase in
the grain size occurring.

This control of the grain is carried out substantially by means
of precipitation of aluminium and/or niobium nitrides and
carbonitrides. In order to produce this control, a significant

presence of these two elements is therefore required, as well as nitrogen at a content which is substantially higher than that which is generally produced following a production operation carried out under normal conditions.

The aluminium content must be between 0.010 and 0.045%. In addition to its grain control function mentioned above, this element controls the deoxidization of the steel and the purity thereof in terms of inclusions of oxides. At less than 0.010%, the effects thereof, from the above perspectives, would be insufficient. At more than 0.045%, the purity in terms of inclusions of oxides risks being insufficient for the applications which are primarily intended. The preferred range is from 0.010 to 0.035%.

The niobium content must be between 0.010 and 0.045%. At less than 0.010%, the effect of grain control would not be sufficient, in particular for the lowest contents of aluminium. At more than 0.045%, there is a risk of cracks appearing during the continuous casting of the steel, in particular if interaction with the phosphorus can occur, as has been indicated above. The preferred range is from 0.015 to 0.045%, preferably from 0.015 to 0.040%.

In conjunction with the contents of aluminium and niobium as mentioned, the nitrogen content must be between 0.0130 and 0.0300% (130 to 300ppm) so that the desired adjustment of the grain size and shape of the Jominy curve are produced. The preferred range is from 0.0130 to 0.0220%.

If it appears desirable, one or more of the following elements,
which are conventionally known, may be added to the steel in
order to improve the machinability thereof: lead, tellurium,
selenium, calcium, and bismuth in particular. The maximum
contents are 0.10%, preferably 0.07% for Bi, 0.12% for Pb,
0.015%, preferably 0.010% for Te, 0.030%, preferably 0.020% for
Se and 0.0050%, preferably 0.0045% for Ca.

The other elements are those which are generally present in
steel as impurities resulting from the production operation and
are not added intentionally. It must be ensured in particular
that the titanium content does not exceed 0.005%. Because the
steel according to the invention is very rich in nitrogen,
beyond this content of titanium there would be a risk of
formation of coarse titanium nitrides and/or carbonitrides,
which can be seen by micrography, which would reduce the
fatigue strength and impair the machinability. Furthermore, the
titanium would thus capture the nitrogen which would no longer
be available for controlling the grain.

The invention will now be illustrated by means of examples. The
appended Figure illustrates the Jominy curves of four steels
whose compositions are set out in Table 1. The steels A, B, C
and D are reference steels. The steels E, F and G are in
accordance with the invention.

Steel	C%	Mn%	Si%	S%	P%	Ni%	Cr%	Mo%	Cu%	Al%	Ti%	Nb%	N%
A (ref.)	0.236	0.888	0.224	0.015	0.011	0.011	1.194	0.014	0.010	0.021	traces	traces	0.0124
B (ref.)	0.195	1.188	0.069	0.023	0.012	0.208	1.228	0.096	0.162	0.021	traces	0.030	0.0179
C (ref.)	0.192	1.205	0.845	0.029	0.014	0.080	0.995	0.099	0.110	0.025	traces	0.011	0.0110

D (ref.)	0.245	1.215	0.840	0.035	0.012	0.085	0.980	0.103	0.098	0.035	traces	0.012	0.0090
E (inv.)	0.230	1.287	0.920	0.018	0.017	0.201	1.269	0.200	0.211	0.032	traces	0.025	0.0174
F (inv.)	0.201	1.453	1.191	0.041	0.014	0.139	1.381	0.246	0.122	0.031	0.002	0.038	0.0243
G (inv.)	0.241	1.254	0.852	0.015	0.010	0.189	1.121	0.111	0.109	0.012	traces	0.016	0.0141

Table 1 - Compositions of the samples

With sample A, the size α as defined above is equal to 8.7 and
the size ß as defined above is equal to 19.1. They are,
therefore, far above the maximum required by the invention. It
can be seen that the Jominy curve has a very marked point of
inflection.

With sample B, α is equal to 2.38 and ß is equal to 11.1. ß
does not, therefore, comply with the requirements of the
invention and the Jominy curve also has a significant point of
inflection although this steel contains niobium and nitrogen
within the prescribed limits. The basic reason for this is that
the silicon content thereof is insufficient.

With sample C, α is equal to 3.38 and ß is equal to 10.7.
Neither α nor ß are within the prescribed limits and the Jominy
curve has a marked point of inflection. Cr and Mo are just
below the minimum values required and in particular the content
of nitrogen is insufficient.

With sample D, α is equal to 2.845 and ß is equal to 9.5, which
is again outside the prescribed limits. The Jominy curve has a
marked point of inflection owing to the insufficient contents
of Cr and nitrogen.

However, for sample E according to the invention, α is equal to 0.41 and ß is equal to 2.7. The required conditions are satisfied and it can be seen that the Jominy curve is almost rectilinear and has no point of inflection.

In the same manner, for sample F according to the invention, α is equal to 0.23 and ß is equal to 3.7. Similar to sample F, the Jominy curve in this instance is almost rectilinear and has no point of inflection.

In the same manner, for sample G according to the invention, α is equal to 0.83 and ß is equal to 6.6. The Jominy curve thereof is almost rectilinear and has no marked point of inflection.

The behaviour of steels A, B and E in Table 1 during carburizing was also studied under normal temperature conditions and at high temperature.

Carburizing operations at normal temperature (930°C) were carried out at low pressure under similar conditions using cylindrical samples in order to confer a carbon content of 0.75% on the carburized surface. These carburizing operations were followed by quenching operations in a gaseous medium (in this instance in nitrogen, but a nitrogen/hydrogen mixture having 10% of hydrogen could, for example, have been used) under two different pressure conditions: 5 bar and 20 bar. It was thus intended to obtain a surface hardness of from 700 to 800HV and a carburized depth (that is to say, the depth at

which the hardness is 550HV) of 0.50mm. The results are given
in Table 2 (tests at 5 bar) and in Table 3 (tests at 20 bar).

Steel	Surface hardness HV	Carburized depth (mm)	Core hardness HV outside the carburized zone
A (ref.)	760	0.35	263
B (ref.)	760	0.50	408
E (inv.)	780	0.48	426

Table 2: Behaviour during carburising with quenching in
gaseous media at 5 bar

Steel	Surface hardness HV	Carburized depth (mm)	Core hardness HV outside the Carburized zone
A (ref.)	780	0.45	318
B (ref.)	720	0.55	423
C (ref.)	738	0.53	408
E (inv.)	750	0.55	524

Table 3: Behaviour during carburizing with quenching in
gaseous media at 20 bar

These tests illustrate that the reference steel A does not
allow the desired carburized depth to be readily achieved. This
is due to its lack of quenchability.

All three of the reference steels B and C and the steel E according to the invention allow the intended carburized depth to be produced under normal temperature conditions for carburizing.

The deviation ΔHV between the surface hardness and the core hardness is very comparable, for a quenching medium at 5 bar, for the reference steel B and the steel E according to the invention (ΔHV = 352 and 354, respectively) and much lower than it is for the reference steel A (ΔHV = 497). However, for a quenching medium at 20 bar, ΔHV is substantially less favorable for the reference steels B and C than for the steel E of the invention (ΔHV = 297, 330 and 226, respectively). The result is that the residual stresses generated by these deviations of hardness, which are the cause of the deformations when the carburized components are quenched under strict conditions, may be minimized by the use of steels according to the invention.

Finally, the highest levels of core hardness are produced with steel E according to the invention. Therefore, for gear components which are subjected to high levels of stress during operation and for which high levels of mechanical properties are sought (in particular high levels of hardness under the carburised layer and at the core) which are greater than the stresses to which the component is subjected during operation, in order to ensure a high level of fatigue endurance during operation, the steel according to the invention is that which, under given conditions for carburizing, is most suitable for a high level of fatigue endurance during operation.

Carburizing tests were also carried out at high temperature (980°C) on cylindrical samples of reference steels A and D and steel E according to the invention which have been described above. In this instance, the carburized surface again had a carbon content of 0.75%. In the two instances, a surface hardness of from 700 to 800HV was sought and a carburized depth, at a hardness of 550HV, of 0.50mm. The quenching in a gaseous medium (nitrogen) which followed the carburizing was carried out at a pressure of 20 bar for steels A and D and only 1.5 bar for steel E. The results are set out in Table 4. Evaluations of the grain size are also presented in accordance with the ASTM standard.

Steel	Surface hardness HV	Carburized depth (mm)	Core hardness HV outside the carburized zone	Grain size ASTM in the carburized layer	Grain size ASTM outside the carburized layer
A (ref.)	740	0.50	312	7/9	8/9
D (ref.)	735	0.59	461	7/8	8/9
E (inv.)	740	0.70	500	8/9	9/10

Table 4: Behaviour during carburizing with quenching in gaseous media at 20 bar (steels A and C) and 1.5 bar (steel E)

As with the carburizing operation at the normal temperature of 930°C, the two steels allow the intended surface hardness to be achieved.

The invention allows a carburized depth to be produced which is substantially greater than with reference A, although reference A has been quenched under much more strict conditions which are known to increase the carburized depth, all other things being equal.

The deviation in hardness between the surface and the core is substantially less with the invention than with references A and D (ΔHV = 240 for E, 428 for A and 274 for D, respectively). The advantages mentioned above with regard to deformations during quenching following carburizing at normal temperature are also even further accentuated in this instance.

The core hardness is higher with the invention than with the reference, in spite of a much lower pressure for the quenching medium. The consequences in terms of the improvement of the fatigue endurance during operation mentioned above for quenching at normal temperature are also found again in this instance.

Finally, both in the carburized zone and outside the carburized zone, the steel according to the invention has an ASTM grain size which is finer than the reference steels A and D. Owing to this, it is less susceptible to the risks of increase in grain size during carburizing at high temperature. This is a very significant advantage since the increase in size of grain on the carburizing components has an extremely detrimental effect on the fatigue strength at the base of the tooth and on the strength of the carburized components. The steels according to the invention are therefore completely suitable for use in the production of gear components (or for any other components for

which comparable properties are required) which are carburized
or carbonitrided at high temperature, with all the economic
advantages that this brings, without in any way sacrificing the
effectiveness of the components.

Other carburizing tests were also carried out at low pressure
on the reference steel A and on the steel E according to the
invention.

For a low-pressure carburizing operation carried out at 930°C
on steel A followed by gas quenching at 20 bar, 72 minutes of
carburizing are required in order to produce the intended
carburizing depth of 0.50mm for HV = 550. Using steel E
according to the invention, with low-pressure carburizing at
930°C followed by gas quenching (same gas as for steel A) at
1.5 bar, 30 minutes of carburizing are sufficient to produce
the same carburized depth of 0.50mm for HV = 550.

For low-pressure carburizing at a high temperature of 980°C,
carried out on the reference steel A, 30 minutes of carburizing
are required and gas quenching at 20 bar in order to produce
the intended carburizing depth of 0.50mm for HV = 550. A
carburizing time of 20 minutes at low pressure at 980°C is
sufficient to produce the same carburizing depth of 0.5mm for
HV = 550 for steel E according to the invention and with gas
quenching at a pressure of only 1.5 bar. The quenching gas used
for steels A and E is, of course, the same.

This shows that steel E according to the invention allows the
carburizing times to be reduced, both at the normal carburizing
temperature (930°C) and at high temperature (980°C), which

allows the carburizing costs to be reduced (quantity of carburizing gas, carburizing time,…) and allows the productivity to be increased for the production of the carburized components.

The steel according to the invention, owing to the controlled quenchability thereof, also allows the pressure of the quenching gases to be reduced in order to produce an identical carburizing depth, which allows deformations in the carburized components to be further reduced or eliminated and allows savings and simplifications to be achieved in terms of technology for gas quenching components in the chambers of gas quenching furnaces.

Carburizing has also been carried out at low pressure on impact strength samples which have not been notched (dimensions: L = 55mm, cross-section 10x10 mm) at high temperature (980°C); i.e. on reference steel A before gas quenching at a pressure of 20 bar andon steel E according to the invention, but in this instance before gas quenching at a pressure of only 1.5 bar. The desired carburized depths were identical, as was the type of quenching gas. The samples which were carburized and quenched in this manner were then broken by means of impact at ambient temperature. The energy at break results obtained in this manner were, respectively:
- 19 Joules for the reference steel A,
- 29 Joules for the steel E according to the invention.

At the same time, impact strength samples of reference steel A were carburized at low pressure at normal temperature (930°C) in order to obtain the same carburized depth as above. They

were then quenched with the same gas at a pressure of 20 bar. These samples were then broken as above at ambient temperature and the energy at break obtained in this manner was 17 Joules, that is, very substantially less than for steel E according to the invention which was carburized at high temperature.

This indicates that, in spite of the sample of reference steel A having a lower core hardness (312 HV) than steel E according to the invention (500 HV), the toughness of steel E carburized at high temperature is higher than that of reference steel A carburized at high temperature or at normal temperature for the same final carburized depth. That is to say, using a steel according to the invention in order to carry out a high temperature carburization operation which is intended to produce a specific carburized depth, does not impair, but in fact the reverse in the toughness of carburized components which are produced from this steel compared with using a reference steel which has also been carburized at high temperature or at normal carburization temperature in order to obtain the same carburized depth. The discrepancy in terms of core hardness between the two steels is not disadvantageous in this respect. This also indicates that the steels according to the invention are particularly suitable for carburization at high temperature, both for reducing carburization times, increasing productivity and reducing the carburization costs compared with known steels which are carburized at normal temperature or at high temperature. The properties for use obtained with these components, such as the toughness, are not impaired compared with the reference steels.

Under the conditions mentioned above, flexural fatigue samples of steel E according to the invention were also carburized at low pressure and high temperature (980°C) comprising, at the center thereof, a widened U-shaped notch. Carburization was followed by gas quenching at a pressure of only 1.5 bar, both the intended carburized depths and the type of quenching gas being the same as in the tests on impact strength samples. In the same manner, a gas carburization was carried out at the normal carburizing temperature of 930°C on steel A according to the prior art, in order to achieve the same carburized depth as above, on flexural fatigue samples identical to those of steel E. After carburization, they were subjected to an oil quenching operation in order to increase the hardness and strength in terms of flexural fatigue of steel A. The endurance limits of the two batches of samples of steel E and A, which were carburized in this manner, were then compared in terms of flexural fatigue at 4 points; the widened U-shaped notch of these samples being centered in the region of the load applied in terms of flexural fatigue. The flexural fatigue tests were carried out for each steel A and E carburized and quenched under the above conditions for up to 10 million cycles.

Under these conditions, the endurance limit at 10 million cycles for steel E according to the invention was 1405 MPa, and that of steel A only 1165 MPa.

This indicates that using a steel according to the invention in order to carry out a high temperature carburization operation which is intended to obtain a specific carburized depth does not impair the strength in terms of flexural fatigue but is instead very advantageous compared with a conventional

carburization operation which is carried out at normal
carburization temperature on a steel according to the prior art
which has been carburized for the same depth and even quenched
in oil in order to increase the strength thereof in terms of
flexural fatigue.

It should be added at this point that these tests of flexural
fatigue are intended to simulate the fatigue strength of a gear
tooth base, gear mechanism or gear component used in a gearbox
of a motor vehicle. This again indicates that the steels
according to the invention are particularly suitable for high
temperature carburization, both for reducing the carburization
times, increasing productivity, reducing carburization costs
compared with known steels which have been carburized at normal
temperature, without impairing the properties for use obtained
with components, such as the strength in terms of flexural
fatigue of the carburized base of a gear tooth of a pinion or
gear mechanism.